eBubble Detector

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August 1, 2008

Abstract

eBubble is a Research and Development project that aims to use particle tracking in a time projection chamber with cryogenic noble fluids to study the large flux of low energy solar neutrinos produced in the fundamental proton-proton fusion reaction in the sun.

1 Neutrinos

Neutrinos were dreamed up by the famous, or rather infamous physicist Wolfgang Pauli in 1931 in response to an apparent violation of the laws of conservation of momentum and energy in beta decay. The neutrino's existence was later confirmed experimentally by Reines and Crown in a reactor experiment. Neutrinos or the 'little neutral one' is a tiny electrically neutral particle. It interacts only through the weak force, making them practically impossible to detect directly. Currently, they are entered into the standard model as massless, but in the last forty years that they in fact, do have mass, albeit a very small mass. The data supports the interpretation that neutrinos oscillate between the three respective flavors, electron, tau and muon neutrinos. Discovering the mass of the three flavors of neutrinos and the probability of their changing flavors are the subjects of much current study. However, it is not the subject of this current study.

There are three major sources of neutrinos available for experimentalists. There are neutrinos produced in nuclear reactors, which are the result of protons striking some target producing pions and kaons which decay into, among other things, neutrinos. A sort of subset of these are atmospheric neutrinos, produced when particles interact with the earth's atmosphere, producing pions and kons, which then decay into a whole mess of particles,

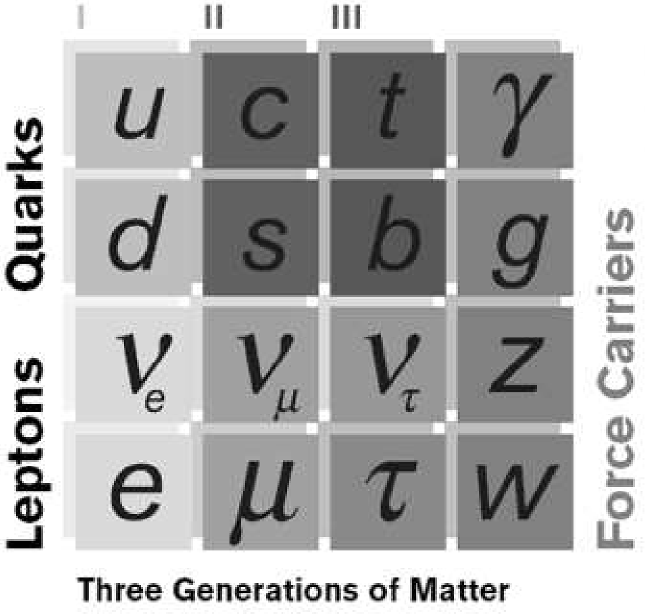

Figure 1: The Standard Model

including neutrinos. And finally, the subject of eBubble's interest, the solar neutrinos.

2 Solar Neutrinos

Solar neutrinos are, as the name suggests, neutrinos produced inside the sun. All of the current ideas about solar neutrinos can be neatly summed up in the standard solar model [1]. It predicts the solar neutrino spectral flux. In stars like the Sun, the largest flux of neutrinos comes from the fundamental proton-proton fusion reaction.

eBubble's particular strength lies in its ability to detect the largest flux of solar neutrinos, and unlike earlier radiochemical experiments, it will be able to measure the neutrino's energy spectrum, and it will measure it in real time.

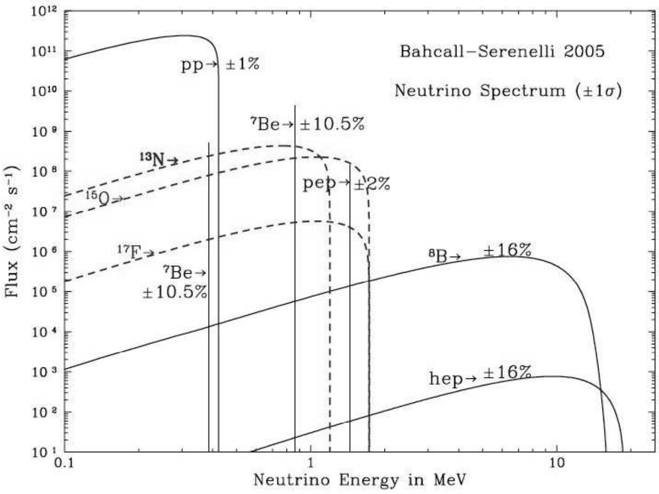

Figure 2: The Standard Solar Model of Neutrino Production. Shows the flux of neutrinos on a log scale as a function of neutrino energy.

3 eBubble

3.1 eBubbles

An eBubble is a quantum mechanical oddity that only exists in non polar fluids at high density Normally, a free electron drifting through a gas is captured by neighboring atoms. However, due to the Pauli exclusion principle,the principle that no two identical fermions may occupy the same quantum state simultaneously, in Noble gases like Helium and Neon, the electron basically blows a nanometer void around itself. It takes more energy for the gas to ionize than it does to maintain this bubble state. Ebubbles have some very interesting properties. For this project's purposes, the most important property is its low mobility. Just like a regular ion, when an electric field is applied, it will drift opposite to the field. And just like an ion, it drifts very slowly through mediums. This works well for our project, because it makes imaging the track much easier. With the electron bubble slow drifts, it allows us to take a series of pictures of our readout as they pass through our two dimensional readout plane. We can then stack the photos and reconstruct the event in three dimensions.

3.2 A Typical Event

In a typical event, a neutrino comes in to the fiducial volume, and scatters an electron from a bulk atom. That electron becomes an electron bubble, and that bubble begins to drift towards a readout plane, according to the applied electric field. The x and y components can be reconstructed from a 2D segmentation of the readout plane, but the z component is a little more difficult. If it was possible to know the time when an event occurred, it could be possible to use the applied electric field to find the z component of the track. In order to reconstruct the z coordinate, we look at the diffusion of the track, based on the Nernst-Einstein equation.

$$\sigma = \sqrt{\tfrac{2kTd}{eE}}$$

Where k is the Boltzmann constant and e is the charge of the electron, T is the temperature of the bulk gas, E is the applied electric field, and d is the absolute drift distance. Both the temperature and the electric field are under experimental control. This means we can both maximize and minimize the diffusion. We minimize the diffusion by lowering the temperature and raising the electric field. But at the same time, we need the diffusion, because we can use the measured diffusion and the Nernst-Einstein equation to measure the absolute drift distance. That absolute drift distance is our z coordinate.

3.3 Gain 101

Just as a camera working in a dark room uses a flash to add light to the scene, we need to amplify our signal to properly read it. We do this using a Gas Electron Multiplier [GEM]. A GEM is a thin sheet of an insulator covered in two foils of copper.In our case, we use CERN GEMs, which use 50 microns of the plastic kapton, with 5 micron copper foils on either side. There are small holes in the surface, and when a voltage is applied across the copper foils, very strong electric fields are set up within the holes.

When an electron is drifted through a GEM hole, it is accelerated. The accelerated electron collides with gas molecules in the hole, exciting or ionizing them. When an atom is ionized, another electron is released to go on to excite or ionize further atoms, creating an avalanche. When these particular excitations de-excite, photons are released. We will be using these photons as our readout. The main emission line we find is the yellow emission line of 585 nm, which is the line that comes from the de-excitation from the 2P1 state to the 1S2 state.

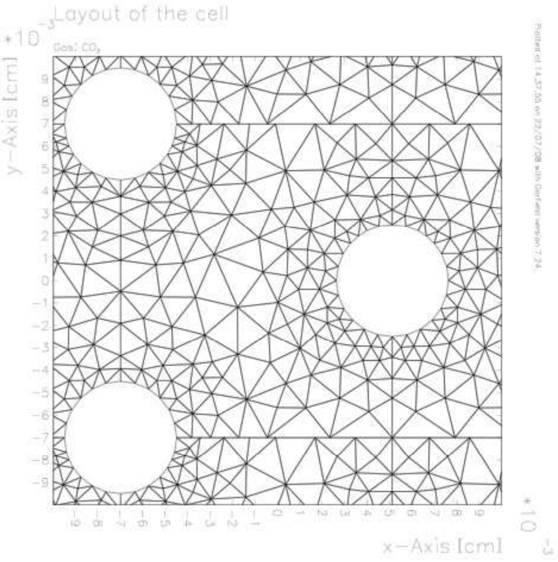

Figure 3: Overhead view of a GEM

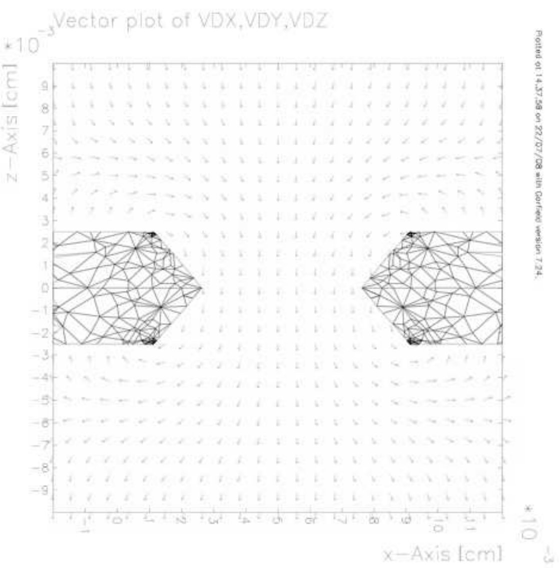

Figure 4: Cross-sectional view of a GEM, and the vector representation of the electric field.

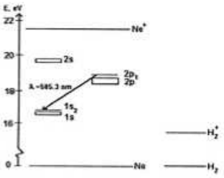

Figure 5: A graphical representation of the transfer from the 2P1 state to the 1S2 state.

$$e + Ne- > Ne^{+} + 2e$$

$$e + Ne- > Ne^{**} + e$$

$$Ne^{**} - > Ne^{*} + \gamma$$

$$Ne^{+} + e^{-} - > Ne + \gamma$$

$$Ne^{m} + H_2 - > Ne + H_2^{+} + e^{-}$$

There are more or less five fundamental reactions going on inside the GEM hole. The first equation is a simple impact ionization. An electron comes in, ionizes a neon atom and releases an electron. The second reaction is an excitation, an electron comes in, excites a neon atom, and leaves again relatively unchanged. But that excited atom can go on into the third reaction, a de-excitation. The excited neon atom loses its excitation energy and releases a photon. In the fourth reaction, a recombination reaction, a positively ionized neon atom is struck by an electron, and the neon captures the electron, releasing a photon in the process. The last reaction is called penning ionization, because it uses a dopant, or penning gas, in our case, hydrogen. Neon can exist in a metastable excited state, an excited state that lasts for a relatively long time. The metastable state's energy is higher than the ionization energy of the dopant, so when it interacts with a dopant molecule, it ionizes it, releasing an electron in the process.

All of this goes to say that we could naively expect to get about one photon per gain electron in our readout.

3.4 Detector Design

eBubble is made primarily of the tracking chamber, the GEM, and a standard CCD camera for our readout. The tracking chamber comes with a great deal of cooling apparatus, and insulation. The chamber is constructed from stainless steel. The steel is as pure as possible to avoid extra radioactive background signals.

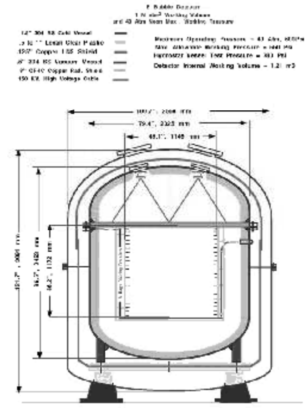

Figure 6: A diagram of eBubble's drift chamber.

The chamber is filled with a cryogenic neon and hydrogen mixture. Cryogenic neon has benefits, not only in tracking, but also in purity. Neon is a pure substance by nature, not easily forming bonds with other substances. And at such low temperatures, all other impurities freeze out onto the walls of the chamber, or freeze and sink to the bottom. We do dissolve a small amount of Hydrogen in the gas mixture, to increase the electron and perhaps the photon gain through penning ionization. We only register events that occur within a smaller fiducial volume, to avoid any background noise from any sort of impurities in the copper of the GEM, or the stainless steel of the chamber walls.

4 Simulations

Most of the work that I have done this summer has been with two separate simulations, Magboltz [3] and Garfield [2]. There are separate simulations to simulate the conditions of the neutrino interaction and diffusion within the chamber itself.

4.1 Magboltz

Magboltz is a program designed to set up the various mixtures of different gases under various pressures, temperatures and externally applied electric fields. The first section of my summer was spent trying to determine whether or not Magboltz itself was doing particle by particle tracking of electrons in gas mixtures, And funnily enough, it looks like it should . It seems to count the number of electrons produced through various ionizations and excitations. It is even possible to count the number of times any certain type of excitation occurs. However, here's the bad news,. While it seems that Magboltz contains all of the ingredients of particle by particle tracking, it cannot do particle by particle tracking as a stand alone program.

4.2 Garfield

But hope abounds, we use another simulation, called Garfield. Garfield uses the Magboltz program to read in the gas mixture conditions. And the best news is, Garfield itself does do particle by particle tracking. Garfield reads in the geometry and field maps of the GEM, written using MAXWELL 3D. From this program, we can extract information about the numbers of excitations and ionizations produced in the avalanche, the locations of those excitations and ionizations, and the energy of the incident electron at each interaction.

In particular, we can find the total number of photon producing excitations, and the ratio of photon producing excitations to the total number of electrons produced. We ran the Garfield simulation for a variety of pressures and Voltages across the GEM, and looked to see what kind of electron and photon gain we should expect under different experimental conditions.

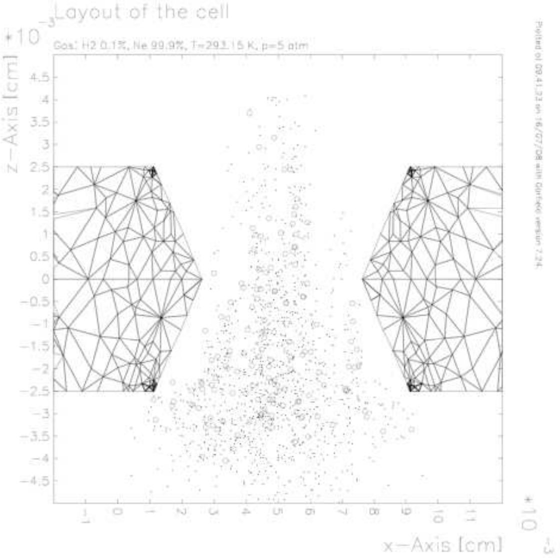

Figure 7: A readout from the Garfield simulation showing the location of excitations in blue and ionizations in red.

Figures 8 and 9 show the number of gain electrons produced in an electron avalanche, and the ratio of the number of 2P1 excitations (or photons) to gain electrons as a function of the voltage applied across the GEM. Each line shows a different pressure, from 1 atmosphere to 9 atmospheres at room temperature, 20 C. In the plot of straight gain electrons, as the density increases, a larger and larger voltage must be applied to get the same amount of gain. In the graph of the photon to electron ratio, as the ratio of the electric field to pressure decreases, the ratio of photons to electrons levels off to about 30%. But this directly contradicts both the prediction made from the five basic reactions occurring within a GEM hole, and the room temperature data that has been taken.

In Figure 10 the light gain normalized to charge gain is shown as a function of charge gain. The ratio is shown to be about one. So why are our simulation results so different from our measured data? There are several possible explanations. Magboltz itself does not account for penning ionization at all, and Garfield does so only in a phenomenological way. The penning transfer efficiency, a measure of the percent of excitations that transfer their energy on to ionizations, can be entered as an input parameter

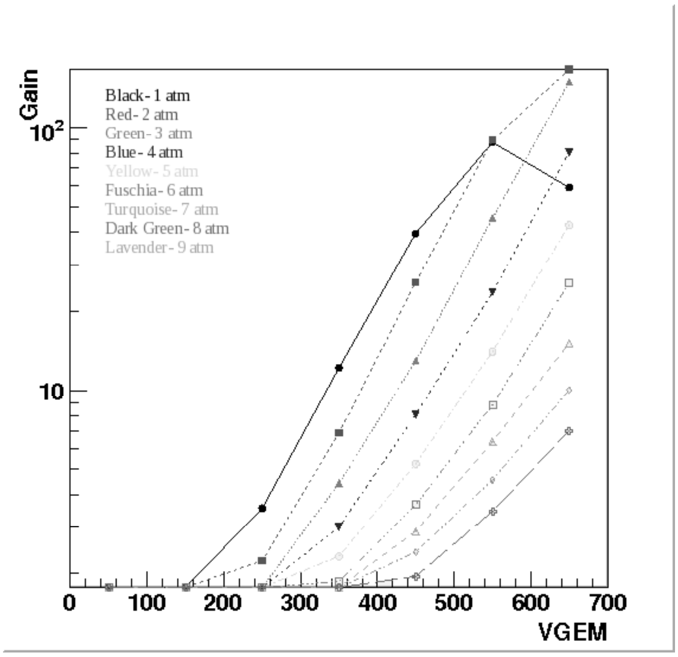

Figure 8: Garfield output graphs of the number of gain electrons on a log scale as a function of the GEM voltage. Each line represents a different pressure. These were conducted in 20C, and with a 99.9% Neon and 0.1% Hydrogen gas mixture.

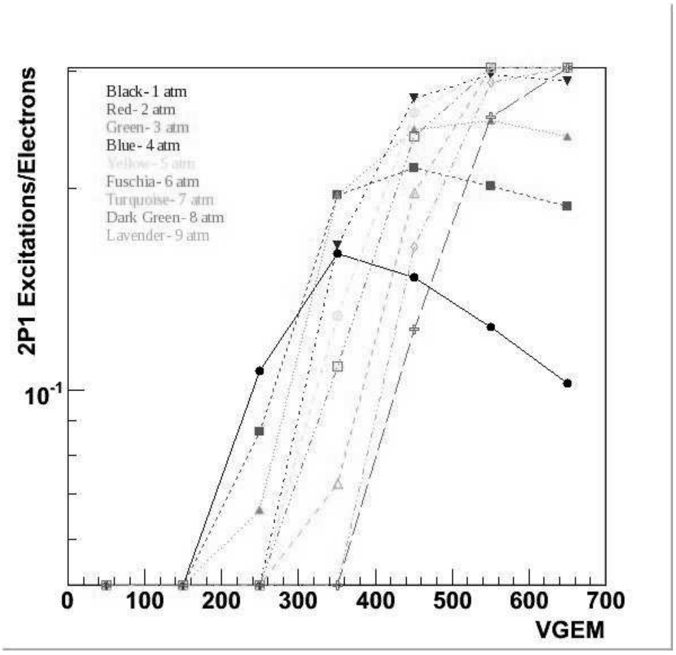

Figure 9: Garfield output graphs of the number of photons produced divided by the number of gain electrons on a log scale as a function of the GEM voltage. Each line represents a different pressure. These were conducted in 20C, and with a 99.9% Neon and 0.1% Hydrogen gas mixture.

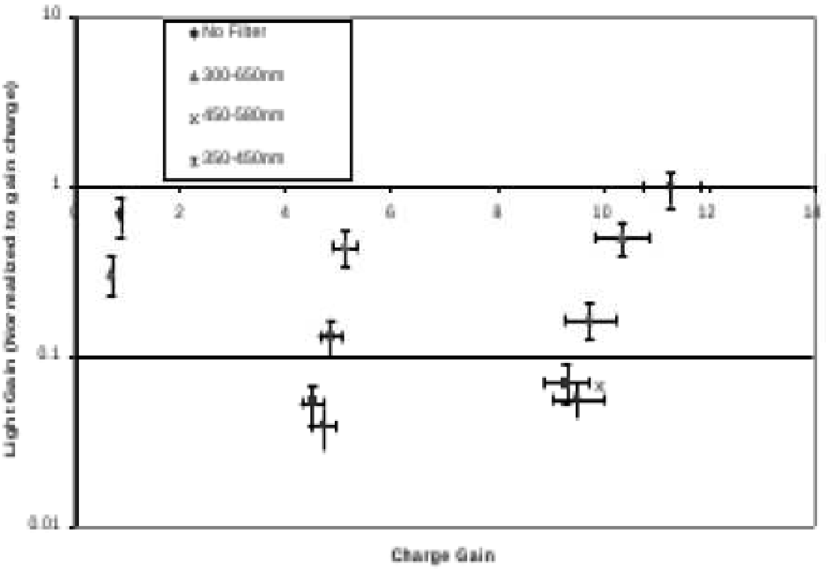

Figure 10: This is a plot of the light Gain normalized to the charge gain as a function of the Charge Gain taken in a 99.99% Neon and 0.01% Hydrogen mixture, under 3 atmospheres of pressure, at 77K, and a 10g/l density. The most important point is the point without a filter that shows a ratio of about one photon to one electron.

in Garfield, but it is clearly not accounting for penning correctly.

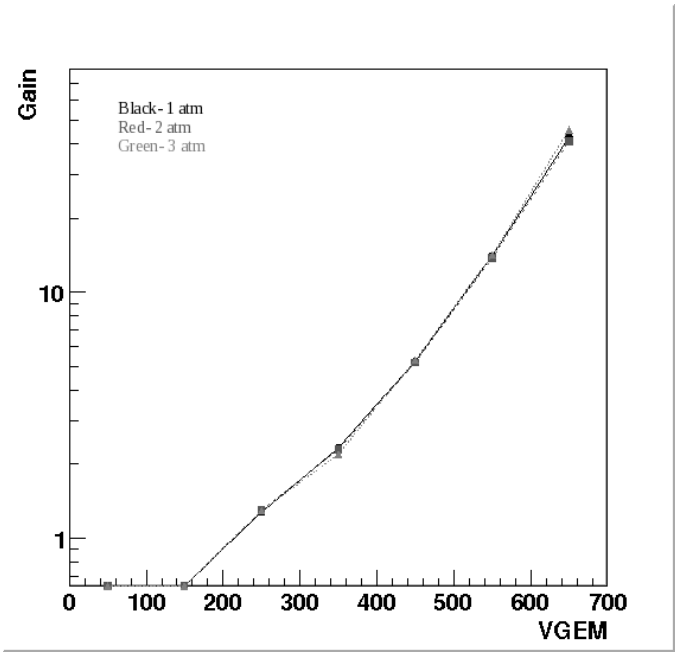

Figure 11: Garfield output graphs of the number of gain electrons on a log scale as a function of the GEM voltage. Each line represents a different penning transfer efficiency rate. These were conducted in 20C, and with a 99.9% Neon and 0.1% Hydrogen gas mixture.

Figures 11 and 12 show charge gain and the ratio of light gain to charge gain as a function of GEM voltage for three different penning transfer efficiencies, 10, 20 and 30%. The data points were collected under 5 atmospheres of pressure and 20 C. However, the different penning transfer efficiencies do not appreciably change the charge gain, or the light gain ratio. We know experimentally that the addition of the Hydrogen dopant gas increases charge gain appreciably. Very little gain, charge or light, is produced without the dopant gas, and therefore the penning ionizations are playing an important role in gain. Also, there are other excitations that need to be taken into account that are not accounted for in Garfield. Garfield does not track excited states, and therefore does not track when an excited state de-excites, sometimes creating photons.

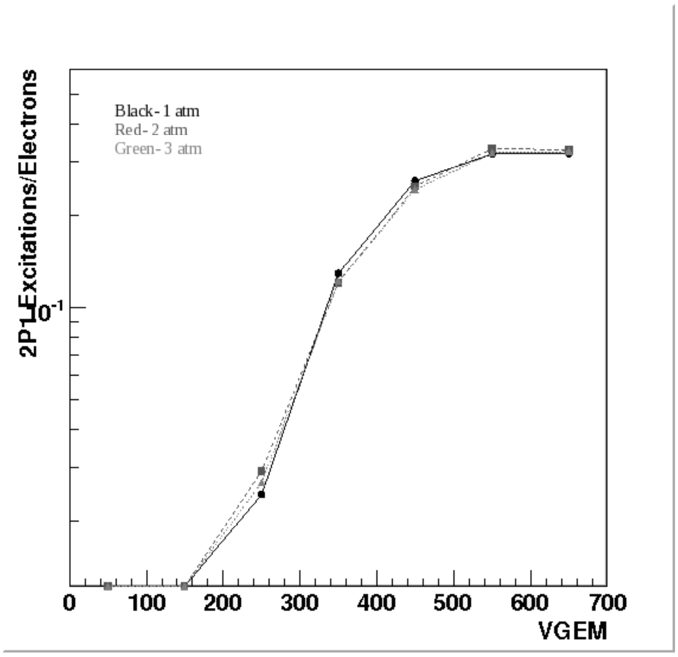

Figure 12: Garfield output graphs of the ratio of the number of gain photons to the number of gain electrons on a log scale as a function of the GEM voltage. Each line represents a different penning transfer efficiency rate. These were conducted in 20C, and with a 99.9% Neon and 0.1% Hydrogen gas mixture.

5 Looking Ahead

So far, we have established the beginnings of a simulation for our readout, where one has never existed before. But simulations for light production in a GEM avalanche need to be extended to accurately account for all excitations and ionizations, particularly penning ionizations. We currently have a kinematic model which takes into account a longer list of 65 possible reactions and can more accurately simulate penning ionization, and the next step is to make this kinematic model interface with Garfield. We will tune this simulation at room temperature and low density, where these simulations were designed to run, and then start to look at low temperatures and critical density, 45 K, 26 atmospheres, or a density of 438 grams per liter. This will allow us to accurately simulate our readout, which puts us one step closer to an accurate, real time, energy-spectrum sensitive, low energy solar neutrino detector.

6 Thanks

I would like to extend my deepest thanks to my advisor, Raphael Galea. I cannot begin to tell everything I have learned from him this summer. I would also like to thank William Willis for the opportunity to work on this wonderful project, the entire staff of Nevis labs, and all of the REU students for all of their help and support, and Reshmi Mukherjee, for giving me the encouragement to apply in the first place.

References

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